HOW CAN SUPERNOVAE TYPE 1A BE USED AS DISTANCE INDICATORS TO REFINE COSMOLOGICAL MODELS

Oindrila Mandal

Oberoi International School, Mumbai, India

ABSTRACT

Background: This research paper explores the use of Type 1a supernovae as distance indicators to refine cosmological models. Type 1a supernovae possess a consistent brightness, making them reliable standard candles for measuring distances in space. By analyzing their luminosity and comparing it to their observed brightness, scientists gain insights into the expansion or acceleration rate of the universe **(Reiss A, 2000 'The case for an accelerating universe from supernovae' *Astronomical society of the Pacific*).** The study of Type 1a smashes has played a vital part in broadening our understanding of cosmological dynamics and refining propositions. Also, this paper discusses the disquisition of the Lambda- CDM model as an abelian frame for comprehending the expansion of the universe. **Type Ia supernovae can only take place under specific conditions which is why they can be used as reliable standard candles.** The research highlights the significance of Type 1a supernovae in refining cosmological models and enhancing our knowledge of the universe's dynamics.

KEYWORDS: Supernovae, CDM, Cosmological Models,

INTRODUCTION

Type 1a supernovae are incredibly luminous phenomena that play a crucial role in astronomy. These supernovae possess a unique attribute — constant brightness. This consistency stems from the explosion of a white dwarf when it reaches a specific mass threshold. As a result, the energy and luminosity released remain unchanged. Scientists utilize this consistency to employ Type 1a supernovae as standard candles for measuring distances in space. By examining their luminosity, we gain insights into. By making repeated measurements of these supernovae, we can refine our understanding of the expansion of the universe. This information is especially important because the data from these supernovae have a lot of uses. In this paper I will investigate how this data can be used to refine cosmological models. Though the Big Bang theory is the leading theory, since the discovery of galaxies that should not be allowed to exist given how old they are according to the Big Bang, brings a lot of question and doubt surrounding the theory which is why it is important to assess the numerous other cosmological models that have been put forward. Since it was the type Ia supernovae that sparked the discovery of the accelerating universe, their data is crucial in verifying these theories to analyze whether they are consistent with the existing framework. Possibly leading to a paradigm shifting discovery.

LITERATURE REVIEW

Astronomers have long sought to quantify the rate of expansion of the universe because it reveals information about its mass density and structure. Two different organizations published research grounded on supernovae in 1998, disputing the extensively held belief that the universe's expansion was decelerating.(Kirshner, R. "Supernovae, an Accelerating Universe and the Cosmological Constant." *Proceedings of the National Academy of Sciences of the United States of America*, vol. 96, no. 8, National Academy of Sciences, Apr. 1999)

This data, still, refocused to an unexpected phenomenon of increased expansion. If confirmed, it would mark a paradigm shift, forcing the start of new propositions to drive the observable expansion and pushing a re-evaluation of cosmological models. Astronomers have viewed the expansion of the cosmos as a fundamental reality. However, the explanations for this expansion have mainly remained hypothetical. Combining Hubble's discovery ,the observations of the expanding universe as well as finding evidence for dark matter (reference), with Albert Einstein's general theory of relativity, which describes the presence of matter, forms of energy, and the curve of spacetime, has altered our present view of the expansion of the universe and its impact on the rate of expansion.

Astronomers can estimate the rate of expansion by using supernovas' brilliance as a function of redshift by studying their brightness and comparing it to their observed brilliance. (reference) Scientists can enhance cosmological models and obtain greater insights into the dynamics of our cosmic environment by repeatedly measuring Type 1a supernovae. The Hubble constant, baryon aural oscillation, and the cosmic microwave background also expose important insights regarding the nature of dark energy and its part in increasing the expansion of the universe. (Dark energy, Hubblesite) The Lambda-CDM (Cold Dark Matter) model is an introductory frame for understanding the universe's expansion. ("LAMBDA - ΛCDM Model of Cosmology") It is occasionally pertained to as the cosmological standard model since it combines the generalities of cold dark matter and dark energy.

The model implies that the universe is homogeneous and isotropic on sufficiently large sizes, which means that matter and energy are slightly distributed and the universe appears the same from any viewing angle. ("Can We Justifiably Assume the Cosmological Principle in Order to Break Model Underdetermination in Cosmology? On JSTOR")

Challenges in Observational Cosmology

Identifying Suitable Observational Objects: One of the significant challenges in observational cosmology is finding objects suitable for observation at high redshifts, where cosmic

effects are substantial and quantifiable. The search for such objects involves identifying celestial bodies that are both observable at high redshifts and have properties that allow their apparent brightness to serve as a reliable indicator of distance. Galaxies, although previously considered potential "standard candles," are not suitable for this purpose due to their rapid evolution over time.

Intrinsic Brightness Scatter of Type 1a Supernovae: These supernovae exhibit an intrinsic brightness scatter that is sufficiently minimal for accurate distance measurements. The low scatter in their intrinsic brightness allows scientists to evaluate the effects of cosmological factors on their observed brightness as a function of redshift. This enables meaningful cosmological measurements with a relatively small sample size of supernovae.

Classification and Origins of Supernovae

Type I and Type II Supernovae: Supernovae are classified into two main types: Type I (SN I) and Type II (SN II). This classification is based on the presence or absence of hydrogen lines in their spectra at maximum luminosity. Type Ia supernovae, which lack hydrogen lines, result from the thermonuclear detonation of white dwarf stars. In contrast, Type II supernovae, along with SN Ib and Ic, originate from the core collapse of massive stars.

Observations and Evidence of Accelerated Expansion

The Hubble Diagram and Accelerated Expansion: Through advancements in observations, the Hubble diagram for Type Ia supernovae has reached higher redshifts, and an increasing number of precise measurements have been obtained. This progress enables scientists to discern the anticipated effects of cosmic deceleration. By comparing the observed light emitted by Type Ia supernovae at specific redshifts in different cosmological models, we can draw conclusions about the expansion rate of the universe. Observations have revealed that distant supernovae appear fainter than expected in a coasting universe, indicating an accelerated expansion during the travel time of their light to our observatories, an observation that was considered opposite to the predictions.

The Calán/Tololo Survey and Distance Precision: The Calán/Tololo survey (Hamuy et al. 1993a) conducted a systematic photographic search for supernovae during specific lunar cycles. Analysis of the survey's results contributed to a comprehensive understanding of Type Ia supernovae and showcased their remarkable precision in estimating distances. A consistent set of photometric and spectroscopic data for different kinds of supernovae were produced by the survey. This dataset made it possible to identify the Phillips relationship, a method that uses Type Ia supernovae as reference luminous objects. It also provided crucial information for building a Hubble diagram specifically for Type II supernovae. It was the calibration of using Supernovae as distance indicators done by this survey that allowed this method of calculating distance to be reliable today. This team also formed a parallel project called the High-Z Supernova search team which in turn was the team that discovered that the universe was in fact accelerating using this method of calculating distance. (add citation)

Spectral Feature Age and Luminosity Determination

Using Spectral Features as Age Indicators: Spectral features present in an SN Ia spectrum, or their absence, can serve as sensitive age indicators. Riess et al. (1997) developed an algorithm to calculate the spectral feature age (SFA) of an SN Ia by evaluating the best fit between its spectrum and a database of SNe Ia spectra with known ages.

Determining Intrinsic Luminosity: The ratio of specific spectral features provides a means to calculate the age of spectral epochs and determine the intrinsic luminosity of the SN Ia. By establishing a relationship between a luminosity/light-curve parameter and these ratios, which are obtained over a range of supernova ages from 6 days before maximum to 20 days after maximum, the estimation strategy is enhanced.

Photometric history and apparent distance moduli: According to Riess et al. (1996), the luminosity/light-curve shape parameter enables the prediction of the expected photometric history of an SN Ia in various passbands. The age estimate determines when a specific photometric epoch occurred during the supernova's history. Apparent distance moduli are calculated by aligning the measured magnitudes on the light curves at the appropriate times. Due to the reddening and gripping characteristics of astral dust, the distance moduli of shorter wavelength bands are anticipated to be original to or lesser than those of longer wavelength bands.

MATERIALS & METHODS

(Table 1) (see appendix A) CMB frame redshifts, peak J-band magnitudes and uncertainties for SNe in the *Hubble* flow.

A consistent set of photometric and spectroscopic data for different kinds of supernovae were produced by the survey. This dataset made it possible to identify the Phillips relationship, a method that uses Type Ia supernovae as reference luminous objects. It also provided crucial information for building a Hubble diagram specifically for Type II supernovae.

Table 2 The best fit for each tested model, including the ΛCMD model. The models are listed in the order from the largest likelihood function value $\mathcal{L}(\hat{\theta}|data)$ to the smallest likelihood of being viable. The reduced χ^2-values are given as an indication of the goodness of fit for a particular model. The AIC and BIC values are shown, as well as the ΔIC for each information criterion. The ΛCDM model is chosen as the "true model"

Model	$\mathcal{L}(\hat{\theta}\|data)$	χ^2	Red. χ^2	AIC	$\|\Delta AIC\|$	BIC	$\|\Delta BIC\|$
Starobinsky	− 120.7052	241.4105	0.6839	253.4105	7.9939	276.7104	23.5272
ΛCDM	− 120.7083	241.4166	0.6762	245.4166	0	253.1832	0
Starobinsky red.	− 122.4442	244.8885	0.6879	250.8885	5.4719	262.5385	9.3553
$\alpha R + \beta$	− 131.2518	262.5037	0.7394	270.5037	25.0871	286.0370	32.8538
Hu–Sawicki	− 140.1668	280.3336	0.7964	294.3336	48.9170	321.5169	68.3336
$\alpha R + \beta R^2$	− 155.0369	310.0738	0.8784	322.0738	76.6572	345.3737	92.1905
βR^n	− 175.0105	350.0211	0.9916	362.0211	116.6045	385.3210	132.1378
$\alpha R + \beta\sqrt{R}$	− 347.0748	694.1496	1.9664	706.1496	460.7330	729.4496	476.2664
$\alpha R + \beta R$	− 488.3049	976.6099	2.7510	984.6099	739.1933	1000.1432	746.9600

Table 2

A paper done by Hough (2020) (Hough R. T *'Viability tests of f(R)-gravity models with Supernovae Type 1A data'* 2020) analysed the redshifts of Supernovae type Ia (Table 1) and compared to different cosmological models as seen in (Table 2)

Supernovae and the Hubble Diagram: Supernovae, particularly Type Ia supernovae, are employed as specific tools to calculate distances in the cosmos. To comprehend the relationship between a supernova's distance and redshift, Hough devised the Hubble Diagram. Scientists can estimate the distance to Type Ia supernovae using SDSS redshift data and a mathematical relationship known as Philip's relationship. This contributes to the calculation of the Hubble constant, which informs us how fast the cosmos is expanding

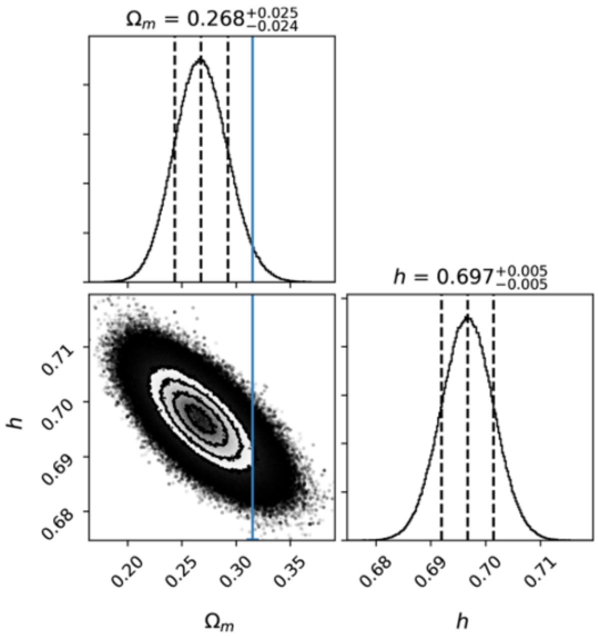
Finding the Best-Fitting Models with Supernovae:

To select the best- fitting cosmological model that directly depicts the universe, Hough calculated a particular model known as the f®- gravity model. Hough used a complex computer simulation known as Markov Chain Monte Carlo (MCMC) to conduct these data runs. This simulation serves as a virtual laboratory for researchers, allowing them to experiment with alternative parameter values inside the f(R)-gravity models and compare them to data from Type Ia supernovae. The MCMC simulation assists in determining the best values for various

cosmological parameters and assures a good fit between the anticipated distance modulus of each f(R) model and observed data from supernovae.

Checking the Simulation with the CDM Model: To validate the accuracy and reliability of the MCMC simulation, Hough compared its results with a well-established model called Cold Dark Matter (CDM). The CDM model serves as a trusted standard against which they can estimate the performance and validity of their simulation (Reiss. A 2017 'The Hubble Constant to 1%: Physics beyond LambdaCDM' *Harvard Health sciences and technology*). By comparing the simulation's issues with the prediction of the CDM model, scientists can gain confidence in the responsibility of their findings and ensure the proper functioning of the MCMC simulation.

(Figure 1) MCMC simulation results

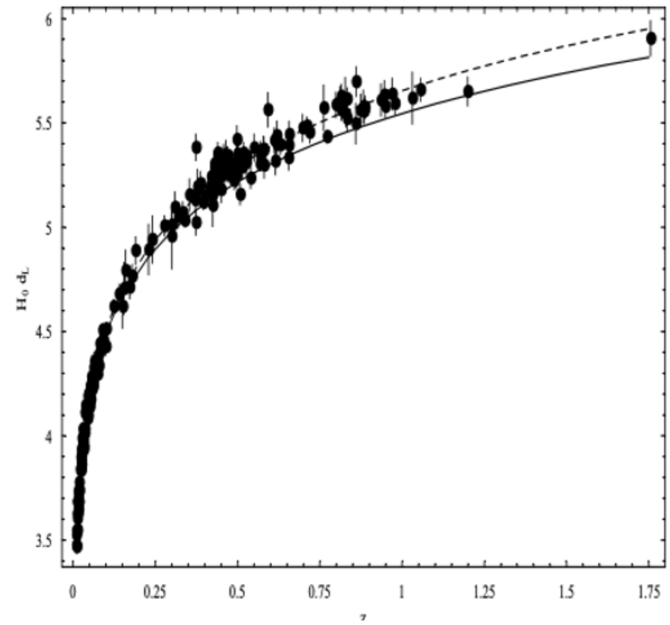


Comparing Different Models: The scientists next compare the f(R)-gravity models to the CDM model, which is widely acknowledged as a trustworthy depiction of the behavior of the universe. They concentrate on two well-known f(R)-gravity models, the Starobinsky model and its simplified version.

Hough examined the level of agreement between the different models by studying the Hubble constants produced by these f(R)-gravity models and comparing them to the values predicted by the CDM model using our dataset. Although the Hubble constants predicted by the Starobinsky model and its simplified variant are marginally lower (albeit not considerably lower) than those predicted by the CDM model, the superior fit of these f(R)-gravity models to the CMB data presents fascinating prospects for future research.

Similarly research done by Nesseris (2018) where they used supernova data with 194 different data points to compare to existing cosmological models to evaluate whether they provide any further insight. The data from this graph (Figure 1) was thoroughly analysed with the cosmological models. The models chosen as seen in (Table 2) include SCDM and LCDM.

(Figure 2) - Supernova luminosity distances with predicted curves. SCDM (continuous line) and LCDM (dotted line) (Nesseris, S., and L. Perivolaropoulos. "Comparison of Cosmological Models Using Recent Supernova Data." *Physical Review* D, vol. 70, no. 4, Aug. 2004)



According to figure 2, the research is looking at how the equation of state parameter, abbreviated as w, changes with redshift for the various cosmological models given in Table 1. Each cosmological model (ansatz) presented in Table 1 has corresponding values of 2min, as shown by the numbers in brackets, which rank each ansatz according to rising values of 2min.The chi-square statistic, which measures how well the model matches the observed data, has a minimal value that's represented by the 2min. Each model's particular values of 2min are given in the parenthetical numbers, along with the rankings of each model according to the 2min values.

For all cosmological models in Table 3, with the exception of the LCDM (Lambda Cold Dark Matter) model, a prior assumption of 0m = 0.3 (where 0m is the present-day matter density parameter) was utilised. A separate best fit value of 0m = 0.34 was used in the instance of LCDM, resulting in a 2min value of 198.745 for that specific model.

RESULTS

Supernovae Type Ia redshift research and comparison with other cosmological theories have revealed some fascinating insights into the behaviour of the cosmos. Using SDSS redshift data and Philip's relationship, the study used the Hubble Diagram to calculate the distances to Type Ia supernovae. This allowed the Hubble constant to be determined and provided insight into the universe' expansion pace.

The f(R)-gravity model was also widely utilised by researchers to determine which cosmological model best captured the behaviour of the universe. The Markov Chain Monte Carlo(MCMC) simulation was used to conduct a complete evaluation that allowed the discussion of parameter values for the f(R)-gravity models. The rigorous comparison with data from Type Ia supernovae allowed for the discovery of the values for numerous cosmological parameters that suit various cosmic phenomena the best. The expected distance modulus of each f(R) model and the observed data from supernovae were excellently fit by the MCMC simulation, demonstrating the correctness of the simulation.

To ensure authenticity, the findings of the MCMC simulation were compared with those of the well- known Cold Dark Matter(CDM) model, which served as a reference. This comparison revealed that the f(R)-gravity models, particularly the

Starobinsky model and its streamlined variant, have slightly smaller Hubble constants than the CDM model. These f(R)-gravity models' greater ability to fit the Cosmic Microwave Background (CMB) data demonstrated that they have a promising future as research tools despite the minor deviations.

In a different study, Nesseris used supernova data with a complete set of 194 data points to assess existing cosmological models and gain additional understanding. As shown in Table 2, the analysis involved a thorough evaluation of the data and comparison with a number of cosmological models, including SCDM and LCDM. This thorough comparison yielded important insights into how well these models fit the observational data.

The findings of both studies have important ramifications for our comprehension of the dynamics of the cosmos. According to the available data, Type Ia supernovae are useful for measuring distances in cosmology and are crucial tools for determining the cosmos' acceleration and expansion rate. Also, the thorough analysis of cosmological models, including the f(R)- gravity models, shows the ongoing development in our understanding of the universe.

DISCUSSION

The exploration highlights the significance of Type Ia supernovae as distance indicators, perfecting cosmological models and extending our understanding of the universe. The Hubble Diagram and the f®- gravity model with MCMC simulation were critical in determining the best- fitting models and their compatibility with the data. Slight differences in Hubble constants were detected when compared to the well-known CDM model, inferring implicit alternate suppositions for cosmic acceleration. Likewise, Nesseris' exploration demonstrated the significance of the data in assessing cosmological models. Overall, these findings contribute greatly to our understanding of the universe's history and stimulate fresh cosmological exploration.

CONCLUSIONS

The study's conclusion emphasizes the significance of Type Ia supernovae in developing cosmological models and expanding our understanding of the universe. The Hubble Diagram and exploration on redshifts have permitted the dimension of the universe's expansion rate. Comparisons with the CDM model indicate interesting differences in Hubble constants. Likewise, the Nesseris study emphasizes the significance of supernova substantiation in refining cosmological models. The study also investigates relation to other models however the CDM model is the more significant in this exploration. Comparison to the f(R)-gravity model also provides further connection between the relation of type 1a supernovae and cosmological models. These discoveries reflect significant advances in cosmology and encourage further exploration into the expansion and structure of the universe.

REFERENCES

1. A. Pinto, P. (n.d.). Type Ia Supernovae as Distance Indicators. stanford.edu. https://www.slac.stanford.edu/econf/C0307282/lec_notes/pinto/pinto.pdf
2. Cosmological Models of the Universe- overview. (n.d.). https://www.cosmotography.com/images/cosmological_modeling_overview.html
3. Dhawan, S. K., Jha, S., & Leibundgut, B. (2018). Measuring the Hubble constant with Type Ia supernovae as near-infrared standard candles. Astronomy and Astrophysics, 609, A72. https://doi.org/10.1051/0004-6361/201731501
4. G. Riess, A. (1998). Observational Evidence from Supernovae for an Accelerating Universe and a Cosmological Constant. Astronomical Journal. https://arxiv.org/pdf/astro-ph/9805201.pdf
5. Kirshner, R. P. (1999). Supernovae, an accelerating universe and the cosmological constant. Proceedings of the National Academy of Sciences, 96(8), 4224–4227. https://doi.org/10.1073/pnas.96.8.4224
6. O'Connor, K. (n.d.). The Lambda Cold Dark Matter Model and Cosmic Microwave Background. boson.physics.sc.edu. http://boson.physics.sc.edu/~gothe/730-F16/talks/KyleO-a.pdf
7. Riess, A. G., Nugent, P., Filippenko, A. V., Kirshner, R. P., & Perlmutter, S. (1998). Snapshot distances to type IA Supernovae: all in "One" night's work. The Astrophysical Journal, 504(2), 935–944. https://doi.org/10.1086/306106
8. Riess, A. G., Press, W. H., & Kirshner, R. P. (1996). A precise distance indicator: Type IA Supernova Multicolor Light–Curve Shapes. The Astrophysical Journal, 473(1), 88–109. https://doi.org/10.1086/178129
9. The Editors of Encyclopaedia Britannica. (2023, June 21). Supernova | Definition, Types, & Facts. Encyclopedia Britannica. https://www.britannica.com/science/supernova
10. The standard model: Lambda-CDM. (n.d.). www.physics.usu.edu. https://www.physics.usu.edu/Wheeler/GenRel2015/Notes/GRLambdaCDM.pdf
11. Type Ia Supernovae | The Schools' Observatory. (n.d.). https://www.schoolsobservatory.org/learn/astro/stars/cycle/ia_supernova
12. file:///Users/sudiptamandal/Downloads/Viability_tests_of_fR-gravity_models_with_Supernov.pdf
13. Nesseris, S., & Perivolaropoulos, L. (2018). A comparison of cosmological models using recent supernova data. University of Ioannina. https://arxiv.org/pdf/astro-ph/0401556.pdf
14. "Hubble's Greatest Discoveries: Accelerating Expansion of the Universe." Sciencefocus.com, 2020, www.sciencefocus.com/space/hubble-space-telescope-accelerating-expansion-of-the-universe. Accessed 15 Nov. 2023.
15. Riess, Adam. "The Hubble Constant to 1%: Physics beyond LambdaCDM." HST Proposal, NASA ADS, Aug. 2017, p. 15145, ui.adsabs.harvard.edu/abs/2017hst..prop15145R/abstract. Accessed 15 Nov. 2023.
16. "Dark Energy." Hubble, Q Starter Kit, 2018, hubblesite.org/contents/articles/dark-energy. Access
17. "Can We Justifiably Assume the Cosmological Principle in Order to Break Model Underdetermination in Cosmology? On JSTOR." Jstor.org, 2023, www.jstor.org/stable/20722507. Accessed 18 Oct. 2023. sed 18 Oct. 2023.